Dr. E. T. Mercanti, 420

RADIOPHYSICS LABORATORY

Thayer School of Engineering

DARTMOUTH COLLEGE

Hanover, New Hampshire

An Experiment to Study Whistlers and Audio-Frequency Emissions with a Receiving System on Board the POGO S-50 Satellite (OGO-C/II) in Conjunction with an Existing Network of Ground-Based Observing Stations

by

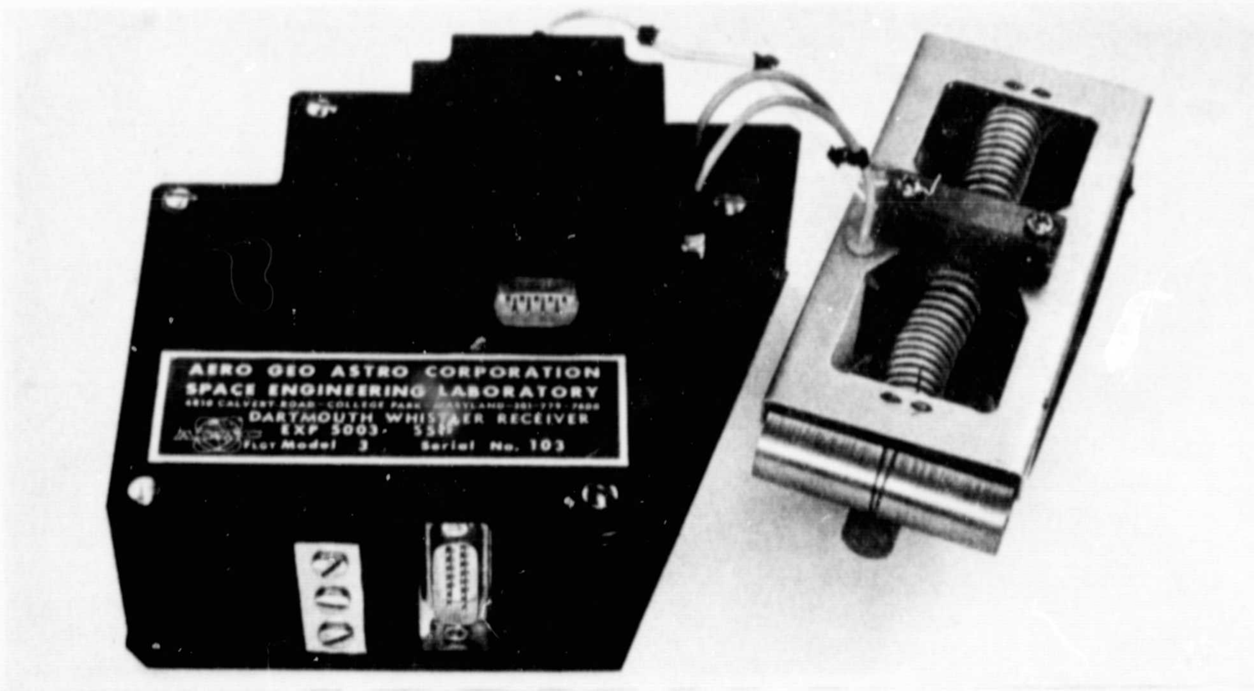
M. G. Morgan and T. Laaspere

Final Report

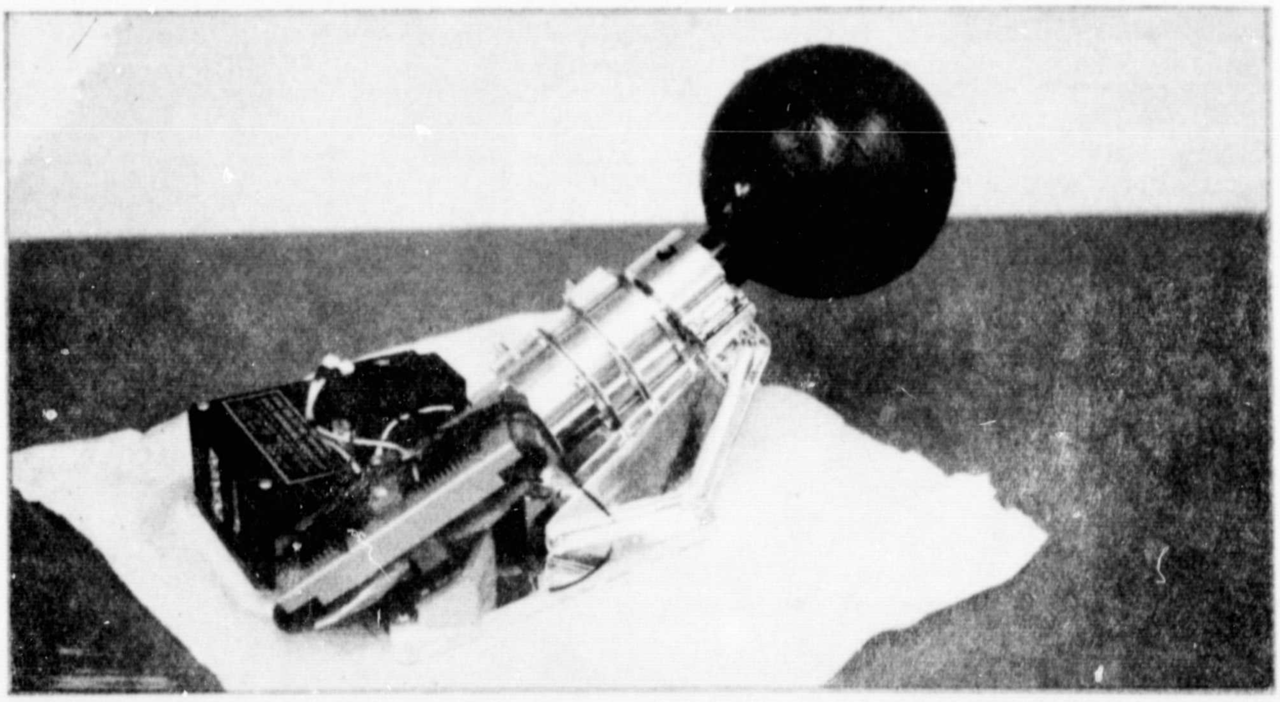
1968 February 29

Prepared for The National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland 20771.

Contract NAS 5-3092



OGO - C/D Experiment-Package and Antenna



OGO-C/D Experiment-Package and Antenna as combined with the Cosmic Ray Ionization Chamber Experiment of H.V. Neher and H. Anderson (Exp. 5007) for mounting on Boom No. 1.

RADIOPHYSICS LABORATORY

Thayer School of Engineering

DARTMOUTH COLLEGE

Hanover, New Hampshire 03755

An Experiment to Study Whistlers and Audio-Frequency Emissions with a Receiving System on Board the POGO S-50 Satellite (OGO-C/II) in Conjunction with an Existing Network of Ground-Based Observing Stations

Contract NAS 5-3092

1963 May 30 - 1968 February 29

FINAL REPORT

1968 February 29

Prepared by

M.G. Morgan and T. Laaspere

for

National Aeronautics and Space Administration

Goddard Space Flight Center

Greenbelt, Maryland 20771

SUMMARY

Technical specifications developed by the contractor for the experiment are cited and a chronological account is given of the production of the experiment by a subcontractor and its acceptance by Goddard Space Flight Center. The launch and the results obtained with the experiment are described, and a resulting scientific paper "Observations of lower-hybrid-resonance phenomena by Dartmouth's OGO-II experiment" is attached.

Consideration which was given to means to acquire data from the spacecraft over Labrador is also described. For various reasons, the matter was abandoned.

TABLE OF CONTENTS

Construction and acceptance of the experiment for flight

Subsequent to receipt of a contract from NASA, we awarded a subcontract to the Aero Geo Astro Corporation (AGAC) to "provide all materials, personnel, services, and facilities necessary for the development and fabrication, testing, check-out and pre-launch field services for instrumentation" for this experiment according to specifications written by us and included in the subcontract, and in accordance with all interface and other relevant NASA specifications. The subcontract with AGAC called for:

One flight-quality prototype unit

Three flight units (to equip OGO-D also)

Two sets of ground support equipment

It was specified that the instrument package should consist of:

A balanced electric dipole antenna approximately 10 ft long overall.

A network to match the antenna impedance approximately to the input impedance of the first amplifier over the range 0.5 - 30 kHz.

A push-pull input amplifier.

A band-pass filter with an adjustable low-frequency cut-off to be finally fixed on the basis of a test to be conducted by the Subcontractor before launch to determine the level of

spacecraft-generated noise,and a high-frequency cut-off to be chosen on the basis of tests conducted by the Subcontractor to be as high as feasible for incorporation into the 57 - 97 kHz FM modulation band of the "Special Purpose" FM-PM telemetry system assigned to our experiment.

A second push-pull amplifier.

A "signal conditioner", including a voltage-controlled oscillator (i.e., an FM modulator), to "condition" the signal for presentation to the Special Purpose telemetry system in the assigned FM modulation frequency band, 57-97 kHz, and with a peak-to-peak amplitude close to but not exceeding 5 volts. It was specified that the "signal conditioner" be designed so as to have as little deleterious effect as possible on the frequency response and signal-to-noise ratio of the experiment, yet meet the Special Purpose telemetry specification and not cause interference to other experiments with inputs to the Special Purpose telemetry below 57 kHz.

A gain control by means of which the gain could be reduced by ground command pulses through the basic facilities of the spacecraft in four 15 db steps arranged so that successive command pulses would

reduce the gain progressively from maximum to minimum in steps of 15 db per command, then return the gain to maximum with the next command, then resume the stepwise reduction, etc.

A calibrating oscillator designed to provide continuous measurement of gain through the whole system at a frequency near 8 kHz, by injection at the input of the input amplifier.

It was specified that the instrument package should perform such that:

The gain after the antenna matching network and before the "signal conditioner" be constant to within ± 1.5 db over the frequency band from 0.5 kHz to the upper cut-off frequency chosen for the band-pass filter.

The signal-to-noise ratio before the "signal conditioner" be at least 3 db with the satellite in an ambient electric field of 10 µv/m intensity (referred to free space), at any frequency within the frequency band given in the foregoing specification and when the noise is the set noise taken over that band.

The dynamic range before the "signal conditioner" be at least 60 db with no more than 5 percent harmonic distortion.

The overall time-constant for recovery after overload, including the "signal conditioner", be not more than 10 msec.

The available gain of the system be such that under good operating conditions of the spacecraft-to-ground telemetry system, the "set-noise" of the system measured at the output of the spacecraft-to-ground telemetry system, be 3 db above the noise of the telemetry system. (In hindsight we realize that this specification was hardly practical as written. See p. 21.)

Injection into the experiment of unwanted signals generated on the spacecraft by inverters, the basic ac power facility, and by other sources, be kept as low as practicable by minimizing the leakage flux of inductors and transformers and by filtering the power supply and command-signal connections.

The weight of the whole instrument package, including the necessary support structure, such as a base-plate, not exceed 1.5 pounds and that the volume, excluding the antenna, not exceed 40 cubic inches.

The power be taken directly from the 28 v dc (nominal) basic spacecraft supply and it not exceed 1 watt.

It was specified that the prototype and flight units should be delivered as follows:

Prototype	1963 Oct 15
Flight Unit No. 1	1963 Dec 15
Flight Unit No. 2	1964 Feb 15
Flight Unit No. 3	1964 May 15

AGAC noted that the reactance of an "electrically short" dipole is capacitive and is given by

$$X_c = \frac{120}{\beta \ell} \left(\ell n \frac{2\ell}{a} - 1\right) \qquad \text{(See footnote)}$$

where ℓ = the dipole half-length

a = the cylindrical dipole radius

$\beta = \frac{\omega}{v}$; $\omega = 2\pi f$; f = frequency; v = phase velocity

Taking $2\ell = 3.05$ m and $2a = 1$ cm as representative of the antenna to be used, one obtains:

$$X_c = \frac{20 \times 10^9}{f}$$

if the free-space value of the phase velocity is used (3×10^8 m/sec).

Footnote: The form of the expression for the input reactance of a thin electric dipole antenna with sinusoidal current distribution is the same as that for an open-circuited, lossless transmission line: $Z_k \text{ ctn } \beta\ell \cong Z_k \frac{1}{\beta\ell}$ when $\beta\ell$ is small. Z_k is the characteristic impedance of the transmission line and in the case of the antenna is an "average characteristic impedance" given by $120 \left(\ell n \frac{2\ell}{a} - 1\right)$. For the derivation of this expression for the average characteristic impedance see, for example, E.C. Jordan's Electromagnetic Waves and Radiating Systems, Prentice-Hall, 1950, Chapter 13.

At the lowest design frequency, 500 Hz, this amounts to 40 megohms and AGAC undertook to design a low noise, push-pull input amplifier with an input impedance of even greater value so as to bridge this impedance. It found this to be an impossible task with transistors, even with the field-effect types which had become available, but did develop a successful design using push-pull type CK587 electrometer tubes transformer-coupled to the transistors. In this design AGAC used 50 megohm grid-to-ground resistors totalling 100 megohms between grids.

We subsequently pointed out to AGAC that the phase velocity of the waves which the antenna was intended to receive would not have the free-space value but would be substantially less, being the free-space value divided by the index of refraction for whistler-mode waves. The index of refraction for this mode, the longitudinal extra-ordinary wave, is given by

$$n^2 = 1 + \frac{X}{Y-1}$$

where n = index of refraction

X = plasma frequency normalized to wave frequency, quantity squared

Y = gyro-frequency normalized to wave frequency.

For values of X and Y appropriate to the ionospheric height of the satellite, say an electron density of $10^5/cm^3$ and a gyro-frequency of 10^6, this leads to an index of refraction of

$$n = \frac{2.84 \times 10^{3}}{\sqrt{f}}$$

Dividing the antenna reactance by this quantity leads to

$$X_c = \frac{7.15 \times 10^{6}}{\sqrt{f}} \text{ ohms}$$

from which one obtains 320,000 ohms at 500 Hz. Thus it seemed feasible to lower the input grid resistors substantially without losing signal voltage, yet reducing the noise voltage proportionately. As a consequence of these considerations, the 50 megohm resistors were lowered to 100 kilohms.

AGAC's progress report for the third quarter of 1963 showed the distortion as a function of modulating frequency for various amounts of deviation of the voltage-controlled oscillator centered in the assigned 57-97 kHz band when the FM sidebands are clipped as required to confine the FM spectrum to the 57-97 kHz band. This is a quite complicated analytical problem and these experimental results presented us with easily understood information for making a design choice. After review and discussion, we selected 10 kHz deviation as the best compromise between greater deviation which would produce better signal-to-noise ratio but greater distortion with increasing modulating frequency due to sideband clipping, and less deviation which would produce poorer signal-to-noise ratio but permit higher modulating frequencies without excessive distortion.

The maximum modulating frequency which can be recovered, irrespective of the amount of distortion, is that whose first-order sidebands are still contained within the allowed 40 kHz of FM spectrum and is, therefore, 20 kHz.

The decision on the amount of FM deviation was made during a general review of progress at AGAC on 1963 Oct 22 with representatives from Dartmouth attending. Although the prototype delivery date of Oct 15 called for by the subcontract had not been met, it appeared that progress was not lagging seriously. However, as matters developed, the prototype was not finally delivered to Goddard Space Flight Center for acceptance tests until 1964 Mar 17, and then with a known deficiency. In AGAC's own environmental tests conducted in late February, it was found that the gain-change sequence did not proceed properly at the required low temperature limit of -10°C; the difficulty began at -5°C. Because the prototype delivery was then almost six months late, and it would require un-potting to fix it, NASA agreed to accept the prototype with the deficiency with the understanding that the flight units would not be accepted without performing satisfactorily at -10°C.

Testing of the prototype at Goddard confirmed the erratic behavior of the gain-change sequence at low temperatures and revealed two additional difficulties: poor high-frequency response of the receiver and a very excessive level of receiver noise. We advised AGAC of these additional deficiencies on April 8. Then on May 4 the unit failed under a vibration test. The failure proved to be a broken weld-joint and was repaired by AGAC.

Corrections to the circuit design were made by AGAC during April and May and the first flight unit was constructed during June and July. Upon potting, the noise problem returned. After this problem had appeared in the prototype, the breadboard model was re-checked and found to be satisfactory. The problem in the prototype had not been conclusively explained and so the flight-unit was constructed without change in this regard. Before potting, it performed satisfactorily. After potting, the noise appeared in this unit. It could only be concluded that potting the electrometer tubes without a heat sink was causing the difficulty. A decision was hastily made to return to transistors on the basis that the original reason for using the tubes had been largely negated when the input impedance had been reduced from 100 megohms to 200 kilohms in view of the reduced antenna impedance anticipated for whistler-mode waves in the ionosphere. A successful re-design using type 2N2483 transistors was achieved within a week and the first flight unit was delivered on August 6 and the second about two months later.*

The third flight unit, though manufactured at the same time as the second, was delayed in delivery an additional three weeks as a result of a request by us to lower its low-frequency

*The schematic diagrams and performance characteristics of the first flight unit are given in the "Progress Report covering 1963 Third Quarter and to 1964 Aug 20" which was forwarded to NASA 1964 Sep 28 and is incorporated herein by reference.

response. On 1964 October 21, we advised NASA that whereas we had set the low-frequency cut-off on our receivers at 500 Hz in view of the high level of interference we expected from the 400 Hz square-wave power supply used by the spacecraft's attitude-control system, results from Alouette I and Injun III had revealed the existence and great importance of proton whistlers in the vicinity of 500 Hz. In view of this, and the fact that there appeared to be some hope that the 400 Hz square-wave interference would not be disabling, and that some reduction in interference on OGO-D could reasonably be expected after experience with OGO-C, we stated our desire to lower the low-frequency cut-off on the third flight unit. The rationale was that the first and second units would serve as a flight unit and back-up for OGO-C, and that whichever of these did not fly would be available along with the modified third unit for OGO-D, giving us a choice for OGO-D to be made on the basis of flight experience with OGO-C. NASA approved this but pointed out that if we were forced to use the back-up unit for OGO-D it would necessarily have a different low-frequency response than the unit we had first elected to use. By omitting the high-pass filter in the third flight unit and by making small circuit changes, AGAC was able to reduce the low-frequency 3 db point to 170 Hz.

In 1964 May, NASA discovered from slow motion picture films of test deployments of our antenna in their large thermal-vacuum chamber, that its mechanical interface specification

for our antenna had not provided enough clearance between our antenna and the solar-array. Accordingly, AGAC was obliged to shorten the antenna by about 6 inches on each end and to rotate its mounting somewhat. In July, NASA requested a further rotation and AGAC again complied.

During 1965 mid-February, a much more serious problem arose in connection with the antenna when NASA advised that the antenna deployment mechanism should be capable of operating down to -150°C rather than -10°C as originally specified. By the end of June, a re-design had been completed by AGAC and qualified at the new specification.

On 1964 December 11, tests were conducted at TRW with the "integrated" spacecraft to determine the mutual compatibility of the four experiments which shared the Special Purpose telemetry system: Experiment No. 2, Stanford (Helliwell); No. 3 Dartmouth (Morgan and Laaspere); No. 5, JPL (Smith and Holzer); and No. 6 GSFC (Heppner). Detectable signals were found to be present in the output of our experiment from all other experiments using the Special Purpose telemetry, ranging from practically negligible in the case of Experiment No. 5, to extremely severe in the case of Experiment No. 6. As a consequence of the latter problem, NASA arranged to have a relay installed so that Experiment No. 6 could be disconnected from the Special Purpose telemetry by ground command. Although the Special Purpose data for this experiment was very much desired by the experimenter, it was redundant with data obtained

from the "Wide Band" (digital) system and he could survive without it. Also, Experiment No. 6 was coupled to the Special Purpose telemetry through a transformer and the experimenter believed that much of the harmonic content of his signal might be developed by overdriving the transformer. He arranged subsequently to by-pass the transformer so that his coupling to the telemetry system would be resistive.

On 1965 May 14 at the TRW test site at Malibu, California, it was discovered that the operation of the telemetry transmitter whose antenna was located on the same boom as our experiment ("Wideband B transmitter, Omni 1 antenna"), was deleterious to the operation of our experiment. Only then did we realize that we had failed to include any specification in our subcontract with AGAC to require protection against high RF fields from the telemetry transmitters. Tests conducted by AGAC after this problem was discovered, showed that our receiver was in fact essentially insensitive to an unmodulated or FM-carrier, but showed some sensitivity to AM modulation, suggesting that it was the residual AM modulation on the telemetry transmitters that caused the difficulty. The problem was never corrected and TRW recommended that our experiment be protected during in-flight operation by using the Wideband A transmitter and the Omni 2 antenna exclusively so long as possible, and that the Special Purpose transmitter, which could be switched to either the Omni 1 or the Omni 2 antenna, and which could be operated simultaneously with either Wideband transmitter on the same antenna,

also be used only on Omni 2 insofar as possible. This recommendation was carried out during the in-flight lifetime of the spacecraft and was successful in eliminating this source of degradation to our data. In flight we found that we did see modest interference during tape recorder playback but this was more likely via internal paths than via the rf output of the Wideband A transmitter on the Omni 2 antenna.

Launch and results

OGO-C was successfully launched from the Western Test Range on 1965 Oct 14 at 1312 Z, thereby becoming OGO-II. Our antenna was commanded to deploy on Revolution No. 75. After careful study of the data records obtained during the command, we cannot be certain that the antenna deployed properly, there being no noticeable change in signals received by the experiment when the command was given. What is more, on OGO-D/IV, by contrast, there was a very marked increase in signals received when the deployment command was given. We did however, in the light of the OGO-II deployment experience, and with the benefit of OGO-II flight experience, take pains to obtain more favorable conditions for observing deployment of the OGO-IV antenna.

In the early days of in-flight experience with our experiment on the OGO-II spacecraft, we found the interference from the harmonics of the 400 Hz square-wave so overwhelming that it seemed that the experiment would be useless. By stepping the gain, we found that in the highest gain position the experiment

was disabled by the interference and in the lower gain positions the interference level greatly exceeded the level of the natural signals. For an unexplained reason, only the even harmonics of the 400 Hz wave were seen.

The spacecraft, launched into polar orbit at dawn, remained in continuous sunlight for some time. Later, when we began to obtain records from eclipse periods, we found, to our delight, that the 400 Hz harmonic interference vanished. In fact we found that we could tell from our records within less than 10 seconds when the spacecraft passed into or out of eclipse. Then, tests of OGO-D at Malibu revealed why this was. The tests were conducted with the batteries sitting outside the spacecraft. On a hunch, our Research Associate, Mr. Blanchard Pratt, asked to have the batteries placed inside the main body of the spacecraft with the doors closed, whereupon the 400 Hz harmonic interference dropped 20 db. Then we realized that when the flying spacecraft is in sunlight and the solar panels are charging the batteries, they are connected directly to the batteries which in turn are connected directly to the 400 Hz square-wave obtained by chopping the dc bus voltage. When the spacecraft is in eclipse and the solar panels are not charging, they are isolated from the batteries by diodes so that the batteries cannot discharge into them. Thus, the path of the interference is from the batteries via the solar panels to our antenna. An investigation by Canadian workers of similar interference in the VLF receiver on Alouette I, revealed that the interference was spin modulated,

dropping out briefly during each spin rotation of the spacecraft. As with our experiment on OGO-II, they had an electric dipole antenna. They deduced that the voltage induced in the antenna as it moved across the flux of the geomagnetic field, caused a plasma current to flow between the antenna and the solar array and that the dropout of interference which occurred with each spin revolution of the spacecraft occurred when the antenna came into the plane defined by the magnetic field vector and the velocity vector of the spacecraft so that no voltage was induced in the antenna.*

Eventually we found that under some conditions of spacecraft operation, we could even get some useful daytime data. In this respect, the attitude control problems encountered by OGO-II may in fact have helped us because they resulted in less use of the attitude control system and therefore less use of the 400 Hz power system.

The following NASA ground stations are equipped to receive the 400 MHz telemetry from the OGO spacecraft:

	Antenna
Gilmore Creek, Alaska	85 ft parabola
Rosman, No. Carolina	85 ft parabola
Johannesburg, So. Africa	40 ft parabola
Quito, Ecuador	40 ft parabola
Santiago, Chile	40 ft parabola
Winkfield, England	14 ft ?

*See "Plasma-induced interference in satellite VLF receivers," by F.J.F. Osborne, F.H.C. Smith, R.E. Barrington, and W.E. Mather; Canadian Journal of Physics, 1967(vol. 45), pp. 47-56.

Data from these stations were produced for us by NASA in a format specified by us: 1/4 inch magnetic tape at 15 in/sec in direct analog form (not FM) using two tracks with the data on one track and the time code, both NASA Serial Decimal and Binary Code of Decimals, on the other.

Because the attitude control system did not operate properly, the operation of the spacecraft was very much impaired. The first few months of operation produced our best data. After that, there were many periods of inoperation due to inadequate power from the solar panels and eventually the failure of the batteries. A large fraction of the production tapes sent to us by NASA has been returned because the tapes contain no useful data.

The best and most useful data which we have obtained have come from Rosman, Gilmore Creek, and Johannesburg. Quito appears to have had operational problems and Winkfield's antenna is obviously inadequate in size.

In spite of these difficulties, we have obtained a useful amount of data from our experiment on OGO-II. Short fractional-hop whistlers with dispersions of about five were seen regularly on nighttime passes at all stations and even on daytime passes at Johannesburg. Short whistlers (long fractional-hop) with dispersions of about thirty are seen but long whistlers have been very scarce. When seen, they have always had a very broad and diffuse structure with a dispersion of about seventy. They are much more diffuse than those observed on the ground and have

a much lower dispersion. We have found no coincidences between whistlers observed on the ground and in the spacecraft but this could be due in part to the fact that the ground stations have been operated on a synoptic schedule rather than programmed in accordance with the passages of the spacecraft. We do have them programmed for OGO-D/IV.

Audio-frequency emissions of the types seen on the ground have been observed very rarely by our experiment though they have not been so scarce in the ground-based observations during this period. They have been seen in the spacecraft data mainly from Winkfield and Gilmore Creek but have also been seen on occasion in the Rosman data when the spacecraft was near the northern limit for that station. The material is broadly similar to that usually observed on the ground but much weaker.

The most significant results have been the frequent observation of what we have identified as lower-hybrid-resonance emissions which is the subject of the attached scientific paper. This paper was presented in preliminary form by Prof. Morgan at the 1967 COSPAR Meetings in London and it has now been submitted to the Journal of Geophysical Research for publication. This class of signal, which has never been observed on the ground, constituted some of the most intense signals observed by our experiment.

We have recently obtained data from Stanford's experiment on board this same spacecraft which show conclusively that the lower-hybrid-resonance emissions are not seen with a magnetic dipole antenna. Simultaneous records from their experiment and ours will be included in the final version of our paper.

Consideration of means to acquire data from the spacecraft while over Labrador

In 1964 Fall we initiated inquiries into the possibility of having the OGO UHF telemetry received at the NASA station at St. John's, Newfoundland, so that we could obtain data from the spacecraft when it was over our whistler and audio-frequency emission observing station in Labrador (Knob Lake). We were informed that the St. John's station was not equipped to receive the OGO telemetry and would not be. As an alternative, NASA initiated an inquiry to the Air Force to see if it would be willing to take data for us at its station in New Boston, New Hampshire. The response was negative. Then, with the encouragement of the Experiment Coordinator and Dr. Schmerling at NASA Headquarters, we began serious consideration of establishing our own receiving station at Dartmouth. We felt that the burden of operating such a facility for any protracted length of time would be acceptable to us only if its operation could be programmed to operate automatically so that it would not have to be manned at the actual time of each pass. We developed system-specifications and AGAC verified the reasonableness of these and developed a firm proposal from them to supply an operating system for a fixed price.

The flow of routine "production data" from the NASA stations was slow in beginning but we found that once it begin, we had a big job on our hands in getting set up to deal with it and then simply keeping up with it. This caused us to "drag

our feet" in the matter of establishing our own station even though we had OGO-D and OGO-F to look forward to. Then two factors arose which caused us to abandon the plan altogether in 1966 early Fall. The first of these was the realization that we had designed the system on the basis of having all of the telemetry transmitter power available but that this would not be the case when sharing the telemetry with other experiments. The FM outputs of the several experiments using the Special Purpose telemetry are summed in a resistor and the RMS value of this sum is maintained constant by an automatic gain control. Thus the addition of just one other signal of an amplitude equal to ours would mean that only half of the transmitter sideband power would be associated with our signal rather than all of it as before. Under this condition, we would need an antenna of twice the capture area. Similarly, if we shared with two other experiments, we would need three times the antenna capture area. But a bigger antenna than we had designed for seemed out of the question for two reasons: 1) Dr. Schmerling had indicated the amount of money that he thought could be made available and the proposal already exceeded that somewhat; and 2) a larger antenna would have a narrower beam-width and would substantially increase the precision with which the automatic tracking would have to be performed.

The second factor which caused us to abandon the proposal was that the Bell Telephone Co. of Canada at whose

"tropo-scatter" station at Knob Lake we had been accommodated for many years, informed us that it was closing down its operations there. We had had twelve years' experience at Knob Lake and knew that the problem of finding an alternate accommodation meeting our requirements would be very difficult indeed. Consequently we decided to close our station there, too.

OBSERVATIONS OF LOWER HYBRID RESONANCE PHENOMENA ON THE OGO-II SPACECRAFT

T. Laaspere, M.G. Morgan, and W.C. Johnson

Radiophysics Laboratory
Thayer School of Engineering
Dartmouth College
Hanover, N.H. 03755

(Submitted to Journal of Geophysical Research for publication.)

ABSTRACT

Audio-frequency noise bands of continuous and triggered types which are evidently associated with the lower hybrid resonance frequency of the ionospheric medium have been observed with Dartmouth's whistler receiver using a 9 ft electric dipole antenna on the OGO-II spacecraft at heights up to 1500 km (apogee) and at frequencies up to 18 kHz (upper cutoff of the broadband receiver). Previous reports of observations of such bands have all been from the Alouette satellites which also carry whistler receivers equipped with electric dipole antennas. Although the electric dipole on OGO-II is much shorter than the antennas of Alouette, our results are similar to the Alouette observations. A direct comparison is made of records obtained simultaneously on OGO-II by Stanford's VLF experiment which is connected to a loop antenna, and it is shown that triggered LHR emissions are seen almost exclusively on our experiment with the electric dipole antenna, pointing to an electric character of the waves. A new observation made by our experiment is that the upper cutoff frequency of the lower hybrid resonance noise bands triggered by fractional-hop whistlers occasionally displays an envelope which has the shape of an Eckersley whistler. Whereas the results of the experiment are consistent with the interpretation that the lower cutoff frequency of noise bands triggered by whistlers is the lower hybrid resonance frequency of the ionosphere in the vicinity of the satellite, there is at present no satisfactory explanation of the upper cutoff.

1. INTRODUCTION

The Canadian Alouette-I satellite, launched on September 29, 1962 into a nearly circular orbit at 1000 km, included in its payload the first broadband VLF receiver connected to an electric dipole antenna rather than to a magnetic loop. With its 150-ft long electric dipole and a VLF receiver covering the frequency range 600 Hz - 10 kHz, Alouette-I discovered a kind of VLF noise band which is not observed on the ground [Barrington and Belrose, 1963; Barrington et al., 1963; Belrose and Barrington, 1965; McEwen and Barrington, 1967]. The Alouette-I results also showed that enhancements of this band of noise are occasionally triggered by whistlers [Brice et al., 1964].

This newly discovered noise band was almost immediately associated with the so-called lower hybrid resonance frequency of the ionospheric medium. It was first suggested that the noise band arises from a type of plasma resonance [Brice and Smith, 1964, 1965]. More recently, it has been suggested that the observed lower hybrid resonance phenomena may be due to a propagation effect rather than to an emission effect [Smith et al., 1966; Shawhan, 1966]. In both interpretations, the local lower hybrid resonance frequency appears as the low-frequency cutoff of the noise bands.

An electromagnetic wave propagating in a cold magnetoplasma at the lower hybrid resonance frequency f_{LH} of the medium becomes wholly electric as the wave-normal becomes perpendicular to the impressed magnetic field (see Appendix). A very large E/B ratio would explain why LHR noise bands were not detected by the Vanguard-III experiment [Cain et al., 1961] and why these bands were very uncommon in the Injun III data [Gurnett and O'Brien, 1964; Gurnett, 1966], for the receivers in both of these experiments were connected to magnetic dipole antennas. However, with our receiver on OGO-II which was connected to an electric dipole antenna, lower hybrid resonance phenomena were among the most intense natural signals observed. A comparison with the Alouette results is thus made possible for the first time.

OGO-II was launched on October 14, 1965 from the Western Test Range into a polar orbit (initial inclination 87.4°, perigee 413 km, apogee 1512 km). The spacecraft was designed to have its orientation controlled by gas jets and reaction wheels, but rapid depletion of the control gas resulted in a loss of attitude control after 10 days. This had a serious effect on a number of the 20 experiments on board but in the case of our experiment it meant only that the orientation of the dipole antenna in space was not known.

Our experiment covered a wider frequency range (≈ 500 Hz - 18 kHz) than had other broadband receivers in satellite experiments. The receiver was also somewhat unusual in that

it had a nearly linear dynamic response. Since the dynamic range of a linear receiver is comparatively small, four gain-positions that could be controlled from the ground were incorporated to accommodate the unknown range of ambient signal intensities to be encountered. In each gain position an 8-kHz calibration signal of known intensity was generated in the experiment-package and inserted into the preamplifier to serve as a reference level for signals received by the antenna.

In spite of the presence of the calibration signal, we cannot draw significant conclusions about the intensity of the signals observed by our experiment. In the first place, we are not confident that the whole length of the 10-ft long "carpenter's tape" antenna was properly extended. Secondly, the balanced input impedance of the receiver was relatively low (200 kilohms), so that under some conditions a large fraction of the voltage developed in the antenna may have been lost across the unknown series impedance of the antenna. Thirdly, sheath effects and the nearness of the dipole to the body of the spacecraft make it hard to estimate the effective length of the antenna. (The location and orientation of the dipole were such that when it was fully extended, the rotation of one of the solar panels could bring it within a few inches of one tip of the dipole.)

2. EXPERIMENTAL RESULTS

The characteristics of DC, ELF, and VLF electric fields existing in the ionosphere and the magnetosphere are of considerable current interest. This interest has been increased by the reports of Scarf and his co-workers [Scarf et al,1965, 1966, 1968] that on satellites P-11 and OV3-3 they have observed electrostatic and eletromagnetic waves of various unusual types.

Dispersed impulses from lightning which have travelled to the spacecraft via the relatively short path through the lower ionosphere (short fractional-hop whistlers), are by far the most common and intense natural signals which were observed by our experiment on OGO-II. Although not nearly so common, lower hybrid resonance bands are next in intensity, followed by dispersed impulses from lightning in the opposite hemisphere (long fractional-hop whistlers), by multi-hop whistlers, and finally by VLF emissions of the type observed on the ground (chorus and hiss). On a number of occasions our data also contain audio signals which appear to be the modulation of short-wave broadcasting stations. These signals may have arisen from the partial detection of amplitude modulated carriers by overloading of the receiver front end or by non-linear effects in the plasma sheath surrounding the antenna. The latter mechanism is enhanced for carrier frequencies near the plasma frequency [Kawashima, 1967], but in our data the phenomenon is characterized by a fading in and out of a number of

stations heard simultaneously, and we have not yet been able to identify any of the stations involved.

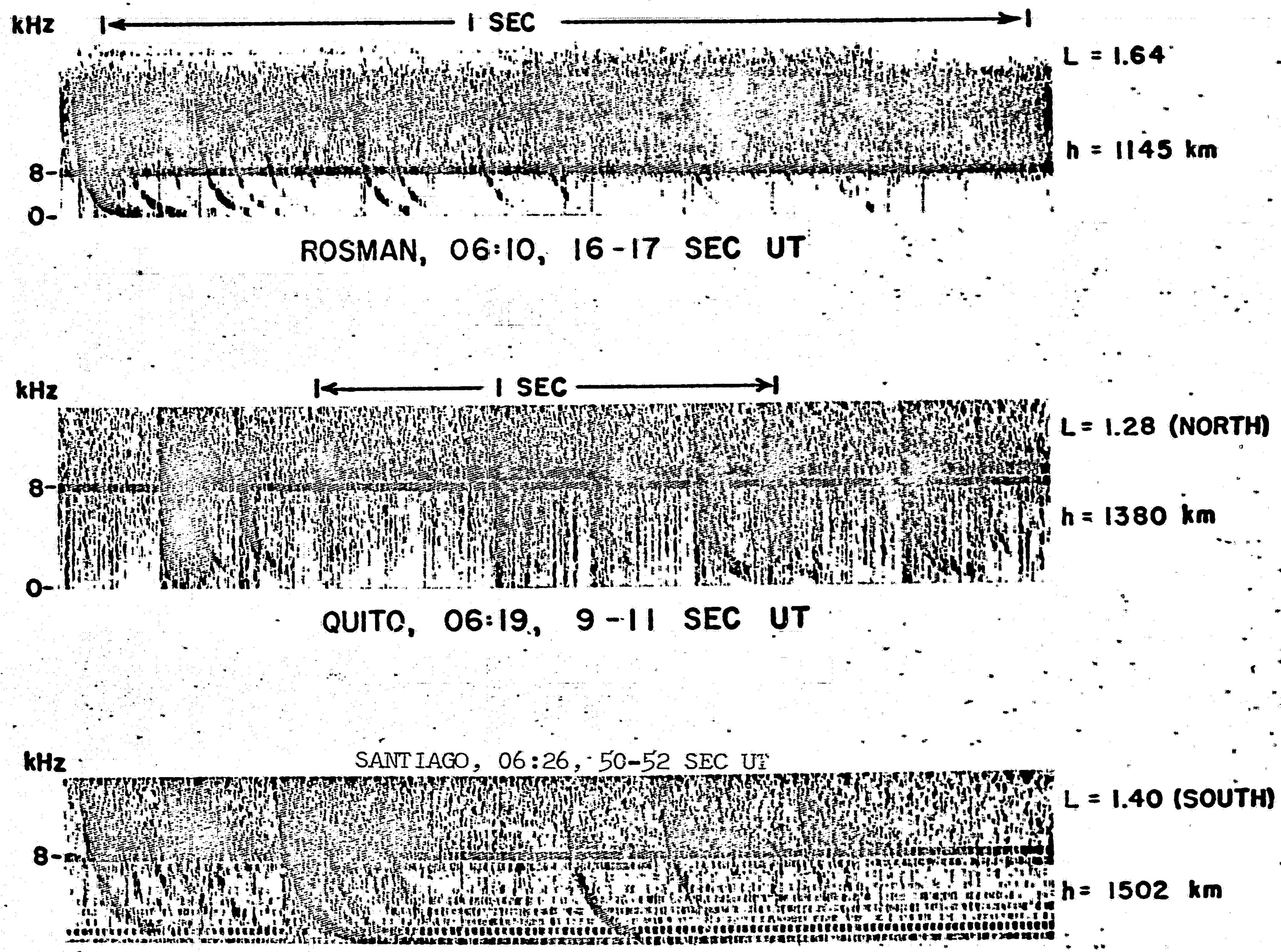
A major problem with the reduction of our data has been its degradation by a high level of spacecraft-generated interference in daylight operation. This interference originated in the spacecraft's 400 Hz power supply which had a square waveform. It was probably coupled to the experiment via the batteries, solar cells, and plasma surrounding the spacecraft through a mechanism such as that discussed by Osborne et al. [1967]. The interference was rich in harmonic content, and was of such intensity in daylight operation when the solar cells were charging the batteries that for much of its lifetime, the experiment had to be kept in its lower gain positions. Unfortunately, with such low gain most of the natural signals of interest went undetected. (For a sample of this interference, see the Santiago record of Fig. 1.)

In addition to the interference generated by the spacecraft itself, our data were also degraded by interference originating in the spacecraft's telemetry system and in other experiments. For this reason only a limited amount of good data is available, and no meaningful statements can be made about the statistics of occurrence of the natural signals detected by the experiment. Nevertheless, some interesting lower hybrid resonance phenomena have been observed on a number of occasions.

Rev. no. 575 (Figure 1)

As the spacecraft passed over the Rosman, North Carolina, telemetry station during this pass on November 25, 1965, numerous short fractional-hop whistlers were observed with whistler-triggered lower hybrid resonance "tails" at around 16 kHz (see top record in Figure 1). As the spacecraft moved southward into the range of the telemetry station at Quito, Equador, near the geomagnetic equator, short fractional-hop whistlers with LHR tails at around 9 kHz, were observed between about 06hr:19min:02sec UT and 06:19:20 UT (01:19:20 - 01:19:20 W 75° Standard Time). Starting at 06:19:09.5 UT a veritable burst of short fractional-hop whistlers with LHR tails was received for two seconds (see middle record in Figure 1). At that time the spacecraft was at a height of 1380 km at the geographic position 7.6°S, 67°W. The L-value corresponding to this position is 1.28 (about 4° north of the geomagnetic equator). Some seven minutes later when the spacecraft was in the range of the station at Santiago, Chile, each whistler observed in the time period 06:26:26 - 06:27:53 UT displayed an LHR tail at the same frequency as at Quito (see bottom record in Figure 1). During this period the spacecraft moved from about 18.5° south to about 23° south of the geomagnetic equator (from L = 1.38 to L = 1.44) and it altitude increased from 1498 km to 1512 km.

The whistlers of Figure 1 have the smallest dispersion in the top display (Rosman), and the greatest dispersion



O-Fig. 1. Whistler-triggered lower hybrid resonance (LHR) emissions observed on rev. 575, November 25, 1965. For the Santiago portion of the pass the spacecraft was in sunlight and the record shows numerous spacecraft-generated interference lines separated by 800 Hz. In this and subsequent figures, the line at 8 kHz is caused by a continuously running internal calibrate oscillator in the experiment.

(about 10 sec $^{1}/_{2}$) in the bottom display (Santiago). (Note that the time and frequency scales are different in the Rosman record from those in the Quito and Santiago records.) Thus the whistlers apparently originated in the northern hemisphere and were travelling southward when they were detected by the experiment.

Rev. no. 672, Rosman (Figure 2)

An interesting sequence of triggered lower hybrid resonance phenomena was observed during this pass over the Rosman station on December 2, 1965, in the period 06hr:52min:00sec - 06:53:35 UT (01:52:00 - 01:53:35 W 75° Standard Time). At about 06:52:00 UT, when the spacecraft was moving southward at a height h of 1080 km and at an L-value of 5.0 (geographic position 49.5°N, 87.6°W, just north of Lake Superior), bursts of an unusual emission were observed for about 1 minute at around 2 kHz. In aural monitoring, these emissions sound somewhat like chorus but sonagraph records show that, unlike chorus, they display an essentially constant emission frequency with time (Figure 2(a)). Inasmuch as these emissions occasionally appear to be preceded by short fractional-hop whistlers (Figure 2(b)), they may well be related to the triggered LHR emissions. Occasionally these emissions come in "stacks" of several levels about 1 kHz apart.

Starting at 06:53:31 UT, with the spacecraft a h=1128km, L = 3.8, numerous lower hybrid resonance tails were triggered

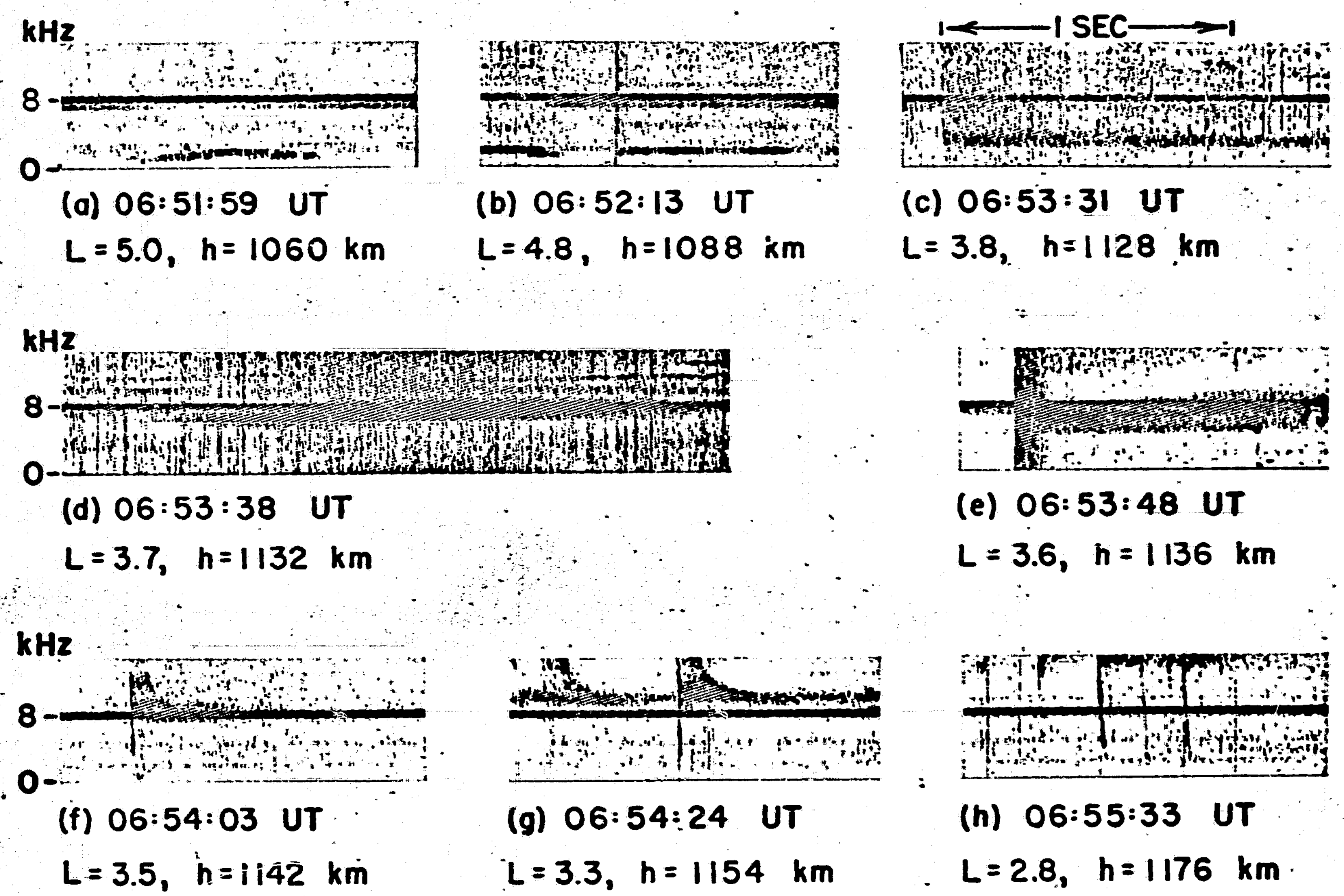


Fig. 2. LHR phenomena observed on December 2, 1965 during rev. 672 of OGO-2 over the Rosman, N.C., telemetry station. Note the increase in the cutoff frequencies of the whistler-triggered LHR tails as the spacecraft moves to lower latitudes.

by what appear to be smeared impulses (probably short fractional-hop whistlers) (Figure 2(c)). Interspersed with these in the same frequency range were noise bands of short duration which were not preceded by impulses (Figure 2(d)). An especially clear case of a triggered LHR tail occurred at 06:53:48 UT (Figure 2(e)).

Beginning at 06:54:03 UT, L = 3.5 (Figure 2(f)), the initiating impulse appeared without smearing as a short fractional-hop whistler and the upper cutoff frequency of the LHR tails clearly displayed an envelope. Note that in the event of 06:55:33 UT seen in Figure 2(h), the upper cutoff frequency of the LHR tail has increased to at least 15 kHz.

If the noise band of 06:53:38 UT was generated by the same mechanism as the triggered emission of 06:53:31 UT, and the lower cutoff frequency of the phenomena was the local hybrid resonance frequency f_{LH} of the ionospheric medium, then there was a large change in f_{LH} in a distance of about 43 km. If we associate the change with the occurrence of the tails at 06:53:31 UT and 06:53:48 UT, then the change must have occurred in a distance of about 100 km.

Rev. no. 1376, Alaska (Figure 3)

In rev. no. 1376 over the telemetry station near Fairbanks, Alaska, (January 22, 1966) the sequence of events started with the appearance of a noise band near 2 kHz at around 08hr:08min:27sec UT (22:08:27 W 150° Standard Time)

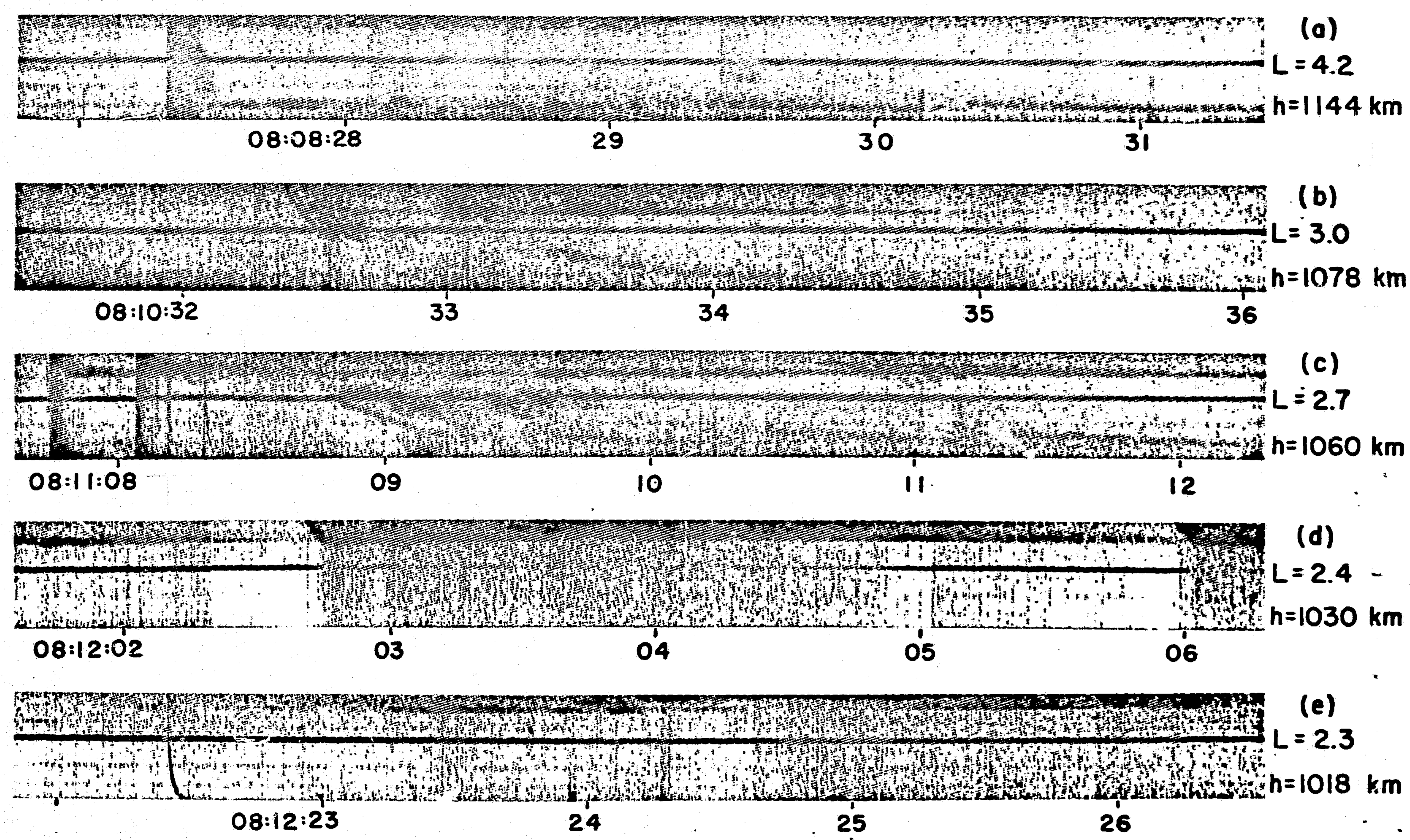


Fig. 3. LHR phenomena observed on January 22, 1966 during rev. 1376 over the Alaskan telemetry station.

when the spacecraft was at a height of 1144 km, L-value 4.2. The noise band displayed enhancements that appear to be related to the occurrence of some smeared impulses (Figure 3(a)). The frequency of the noise band gradually increased to about 3 kHz and then terminated abruptly at 08:09:00 UT (h = 1128 km, L = 3.8). Less than 2 seconds later, smeared impulses occurred with tails between about 5.5 and 7.5 kHz.

As the spacecraft moved to lower latitudes, numerous whistler events were observed which display long triggered tails. The event at 08:10:33 UT of Figure 3(b) appears to represent a hybrid whistler inasmuch as both a long fractional-hop and a two-hop component are evident. The long fractional-hop component of this whistler has a dispersion of about 50 $sec^{1/2}$ and is followed by a narrow, long-duration tail at about 10.2 kHz. In the whistler event of 08:11:10 UT of Figure 3(c) the frequency of the tail has increased to about 11.3 kHz. In the event of 08:12:03 of Figure 3(d) the tail at about 12 kHz becomes the lower cutoff frequency of a noise band that extends to about 16 kHz at 08:12:07. The sharp cutoff of whistlers at the lower boundary of the noise band in Figure 3(d) represents a relatively common phenomenon in LHR events. In the event shown in Figure 3(e) several lines exist in the band between 12 kHz and 16 kHz, but the short fractional-hop whistler seen in the figure is not followed by an LHR tail.

Comparison with the Stanford experiment on OGO-II(Figure 4)

Mr. J. Katsufrakis of Stanford University, has kindly provided us with a record of the Stanford University - Stanford Research Institute VLF experiment on OGO-II, enabling us to make a direct comparison of data obtained simultaneously on broadband receivers connected respectively to magnetic and electric dipole antennas on the same spacecraft. Such a comparison has previously been made on a rocket flight by the University of Iowa group [Shawhan and Gurnett, 1968].

The comparison of the Stanford and Dartmouth records is presented for rev. no. 1444 over the Fairbanks, Alaska, telemetry station (January 27, 1966).

The data of interest start at about 06:28:50 UT (h = 1010 km, L = 5.2) when Stanford picked up a hiss band extending from about 2.5 kHz to 6 kHz. The same hiss band appears in the Dartmouth records as soon as the spacecraft, perhaps by coincidence, enters eclipse and the spacecraft-generated interference subsides (at about 06:29:10 UT). The hiss band shows little change until about 06:31:00 UT (h = 940 km, L = 3.4) when it starts to decrease in intensity.

In the Dartmouth data the band first appears to increase in frequency and then becomes undetectable at about 06:31:16 UT (Figures 4(a) and 4(b)). In the Stanford data the hiss band does not completely disappear and its frequency remains near the second harmonic of the spacecraft's 2461.5 Hz "sync signal."

Figure 4. Comparison of OGO-II records obtained simultaneously on January 27, 1966 by Stanford's loop (ST) and Dartmouth's dipole (DA).

(a) 06hr:31min, 03sec - 11 sec UT, $L \approx 3.3$, $h \approx 932$ km;

(b) 06:31, 11 - 19 UT, $L \approx 3.2$, $h \approx 926$ km;

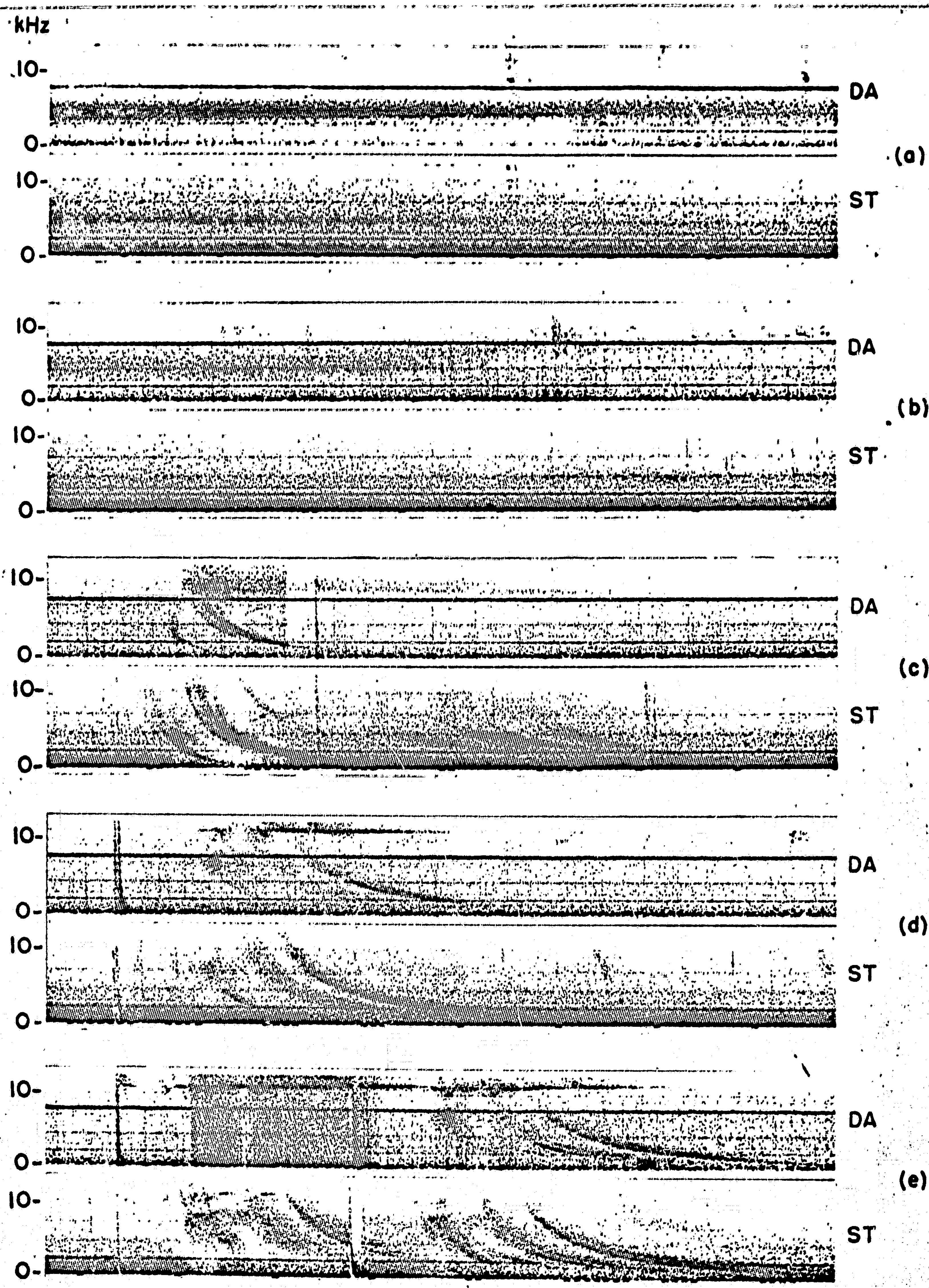
(c) 06:31, 39 - 47 UT, $L \approx 3.0$, $h \approx 916$ km;

(d) 06:33, 21 - 29 UT, $L \approx 2.4$, $h \approx 858$ km;

(e) 06:33, 36 - 43 UT, $L \approx 2.3$, $h \approx 848$ km;

(The period of the time-code pulses that appear near zero frequency in the Stanford record is one second.)

See next page.


kHz
10-
0-
DA
ST
(a)
(b)
(c)
(d)
(e)

This suggests that this noise band might not represent natural hiss but may be spacecraft-induced electromagnetic interference in the plasma surrounding the spacecraft.

In any case, after 06:31:16 UT numerous whistler-triggered LHR emissions appear in the Dartmouth records but, while the associated whistlers as a rule show up better in the Stanford data (their receiving system is considerably more sensitive to electromagnetic waves than ours), the LHR emissions go undetected in their data. The only exception to this is seen in the Stanford record of Figure 4(e), where two short sections of the lower-hybrid resonance line, or possibly some other signal related to that resonance, can be detected at 11.2 kHz. This is perhaps not surprising in view of the fact that the corresponding resonance line shown in the Dartmouth record of Figure 4(e) is perhaps the most intense that we have observed on OGO-II. The almost equally intense LHR events shown in the Dartmouth record of Figure 4(c) for a long fractional-hop whistler, and in Figure 4(d) for what appears to be a hybrid whistler, are not seen in the Stanford records at all. (The abrupt change in the intensity of the LHR tail in Figure 4(c) was introduced by the data processing equipment.)

The observations presented in Figure 4(c)-(e) do not constitute an isolated event that could be explained in terms of relative antenna orientation (the angle between the axis of our dipole and the normal to Stanford's loop is about 55°) and

they are in complete agreement with the report of Katsufrakis [1968] that lower hybrid resonance effects of the type observed by the Alouette and Dartmouth receivers using electric dipole antennas are not seen by receivers using loop antennas. This strongly suggests that the wave fields in these signals are indeed primarily electric as indicated by the results of the cold plasma theory given in the Appendix, and for that reason either are not observed at all, or only very weakly, by the Stanford experiment which has been reported to be highly immune to electric fields [Guthart et al., 1968]. On the other hand, receiving systems equipped with loop antennas may well be preferable for observing the interesting whistler traces of anomalous dispersion which are related to the lower hybrid resonance frequency [Katsufrakis, 1968; Smith and Angerami, 1968].

The "Envelope Effect" (Figure 5)

As first demonstrated by Figure 2, the upper cutoff frequency of LHR tails triggered by short fractional-hop whistlers occasionally displays a well-defined envelope. Three samples of such events are shown in Figure 5 in greater detail, two of them on a frequency scale that includes the upper limit of the frequency response of the experiment. A somewhat similar effect has been observed in the Alouette-I data by Barrington et al. [1965] who speak of the "wedge shape" of triggered noise. What is surprising about these "wedges" in our data is that sometimes the envelope follows

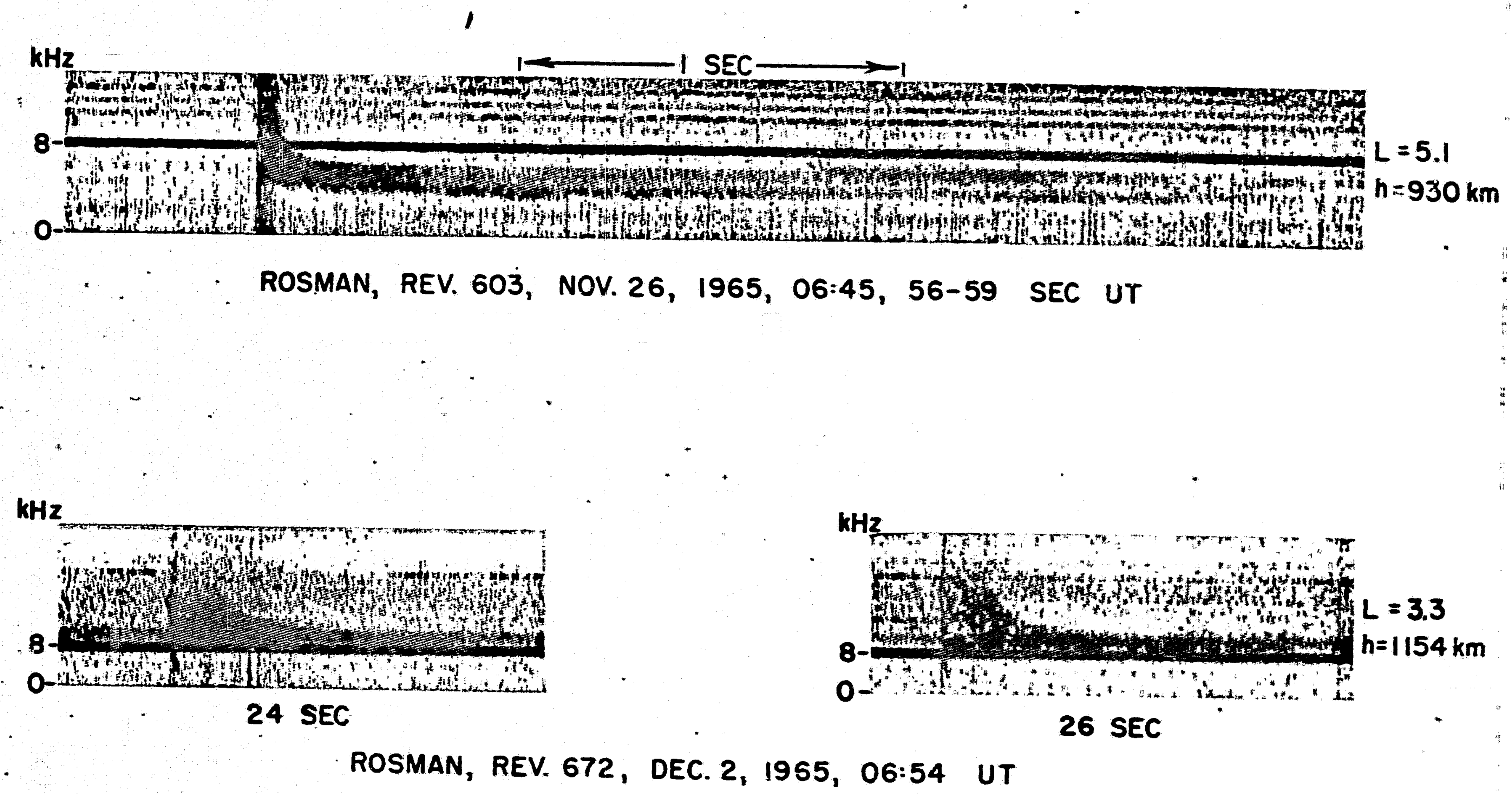


Fig. 5. Samples of LHR tails of short fractional-hop whistlers which display a well-defined envelope of the upper cutoff frequency.

rather closely the simple Eckersley dispersion law of whistlers, $t = D/\sqrt{f}$, if f is taken to be the amount by which the envelope frequency exceeds the upper cutoff frequency of the tail which it approaches asymptotically, and t is taken to be the time delay from the instant when the initiating short fractional-hop whistler crosses the upper cutoff frequency of the tail.

In view of the systematic variation with latitude of the upper cutoff frequency of LHR tails as demonstrated by Figure 2, it is hard to believe that the envelopes are created by some instrumental effect, such as an upward translation in frequency of sub-protonospheric whistlers. It seems more likely that under suitable conditions the envelope is indeed a natural phenomenon. Furthermore, the extremely rapid variation of the envelope such as in the top display of Figure 5 suggests that the envelope must represent a variation of the signal spectrum in time, not in space.

3. DISCUSSION

It would be of considerable interest to calculate the lower hybrid resonance frequency (see equation A8 of the Appendix) using values of the effective mean ion mass number M_{eff} and the electron density N_e determined by direct measurement of these quantities, and to compare this calculated frequency with the lower cutoff frequency of the LHR bands and triggered tails seen in our results. However, the experiments

on OGO-II which were designed to study the ion composition and density were among those most seriously affected by the absence of spacecraft attitude control. Accordingly we have not yet had the opportunity to make this important comparison and it must be postponed until OGO-IV records from these experiments and ours are available.

With the values of M_{eff} and N_e being unknown, we can at least substitute the known intensity of the geomagnetic field at the spacecraft into the expression for the lower hybrid resonance frequency and compute curves of M_{eff} versus N_e for LHR frequencies of interest. The reasonableness of our results can then be judged in the light of what is known about the normal ionospheric composition and density at the location of the satellite in each instance. We have done this and found that the assumption that the lower cutoff frequency of the LHR phenomena observed by our experiment is the local value of the lower hybrid resonance frequency does indeed lead to reasonable results. On the other hand, we find it difficult to explain some of the high values of the upper cutoff frequencies in terms of present theories.

We have shown samples of our data which display changes in the cutoff frequencies of LHR phenomena in time intervals of the order of seconds at L-values near 3.8 (Figures 2 and 3). We interpret these as indications of rapid increases in electron density encountered by the spacecraft as it flys toward lower latitudes near 60° geomagnetic. It is possible that these

observations are related to the rapid increases in electron density starting at about 60° geomagnetic latitude that appear to be a regular feature of the quiet nighttime ionosphere at 1000 km [Brace and Reddy, 1965; Brace et al., 1967]. In view of the rapidity with which the changes take place, however, it seems to us more likely that they are related to the observations of the low-latitude boundary of the very low electron densities in the polar regions that have been studied by Hagg [1967] in the 1500-3000 km altitude range using Alouette-II high-latitude ionograms. Hagg's results, in turn, may be related to the plasmapause which has been observed at much greater heights at around L = 4 - 6 [Carpenter, 1963, 1966; Taylor et al., 1965, Binsack, 1967].

4. ACKNOWLEDGMENTS

This research has been supported by the National Aeronautics and Space Administration under contract NAS 5-3092.

We are indebted to the principal investigator of the Stanford experiment, Prof. R.A. Helliwell, for making possible the comparison of their data with ours.

5. APPENDIX: REVIEW OF THE PROPERTIES OF LOWER HYBRID RESONANCE

Dispersion relations for electromagnetic waves travelling in a cold multi-component magneto-plasma covering the full range of frequencies have been obtained by a number of authors in recent years. A convenient form of the equation is (Stix [1962], p. 12)

$$\tan^2\theta = \frac{-P(n^2-R)(n^2-L)}{(Sn^2-RL)(n^2-P)} \tag{A1}$$

where

n = phase index of refraction

θ = angle between the direction of the static magnetic field and the wave normal

$$R = 1 - \sum_k \frac{X_k}{1+\varepsilon_k Y_k}$$

$$L = 1 - \sum_k \frac{X_k}{1-\varepsilon_k Y_k}$$

$$P = 1 - \sum_k X_k$$

$$S = \frac{1}{2}(R+L)$$

X and Y are the generalized forms of the parameters familiar from the radio approximation where the ionic mass is, in effect, taken to be infinite. That is, X_k is the

square of the plasma frequency of the k^{th} ion species normalized to the wave frequency, and Y_k the gyro frequency of the k^{th} ion species normalized to the wave frequency. ε_k is + 1 if the charge of the k^{th} ion is positive, - 1 if negative.

Equation A1 shows that for propagation perpendicular to the magnetic field ($\theta = 90°$), either $n^2 = P$, or $n^2 = RL/S$. At frequencies of interest, $P < 0$ and the first mode does not propagate. We thus have only the mode for which

$$n^2 = \frac{RL}{S}, \qquad \theta = 90° \tag{A2}$$

Resonance occurs when n^2 becomes infinite. Then $S = 0$, which leads to

$$\sum_k \frac{X_k}{1-Y_k{}^2} = 1 \tag{A3}$$

If the ions are singly-charged and positive, and the plasma is electrically neutral, then the preceding equation can be put in the form

$$\frac{1}{1-Y_e{}^2} + \sum \frac{\alpha_k \frac{m_e}{m_p} \frac{1}{M_k}}{1-Y_k{}^2} = \frac{1}{X_e} \tag{A4}$$

where the subscripts e, p, and k refer to electrons, protons, and the k^{th} ion species, respectively; m denotes the mass of the particle; M the atomic mass; and α_k the fractional concentration N_k/N_e of the k^{th} ion species.

Under most ionospheric conditions the wave frequency at which this resonance occurs, known as the "lower hybrid resonance frequency", is such that $Y_k^2 << 1 << Y_e^2$. In that case

$$\frac{m_e}{m_p} \sum_k \frac{\alpha_k}{M_k} = \frac{1}{X_e} + \frac{1}{Y_e^2} \qquad \text{(A5)}$$

or

$$f_{LH}^2 = \frac{f_{pe}^2 \quad f_{ge}^2}{f_{pe}^2 + f_{ge}^2} \frac{m_e}{m_p} \sum_k \frac{\alpha_k}{M_k} \qquad \text{(A6)}$$

where

f_{LH} = lower hybrid resonance frequency (Hz)

f_{pe} = plasma frequency for electrons

$= 8.984 \times 10^3 \sqrt{N_e}$ Hz, (N_e in cm^{-3})

f_{ge} = gyro frequency for electrons

$= 2.8 \times 10^6$ B Hz, (B in gauss)

If we now define the "effective mean ion mass number" M_{eff} by [Barrington et al., 1965]

$$\sum_k \frac{\alpha_k}{M_k} = \frac{1}{M_{eff}} \qquad \text{(A7)}$$

we obtain

$$f_{LH}^2 = \frac{1}{1836\ M_{eff}} \frac{f_{pe}^2\ f_{ge}^2}{f_{pe}^2 + f_{ge}^2} \tag{A8}$$

It is seen that f_{LH} depends upon the electron density, the intensity of earth's magnetic field, and the ion composition.

In the polar cap region above 1500 km, N_e may occasionally be of the order of 100 cm^{-3} or less [Hagg, 1967]. This depresses f_{LH} so much that the condition $Y_k^2 << 1$ is no longer true for protons. In this circumstance, the concept of mean effective mass number is no longer very convenient because the factor $1/(1-Y_k^2)$ must be included for protons in equation A4.

It should be emphasized that f_{LH} has been defined using the formulas for perpendicular propagation. As the angle between the direction of the static magnetic field and the wave normal is decreased from $\theta = 90°$, resonance still occurs but at increasingly higher frequencies until at $\theta = 0$ the resonance frequency becomes the electron gyro frequency. These and other points are discussed in greater detail by Booker and Dyce [1965] and Smith and Brice [1964].

If the electron density and the earth's magnetic field intensity are known, and the lower cutoff frequency of LHR phenomena is interpreted to be the hybrid resonance frequency of the ionospheric medium in the vicinity of the satellite, and $f^2_{gk} << f^2_{LH}$, then the local value of M_{eff} can be computed

from equation (A8) [Barrington et al., 1965]. However, for a medium consisting of more than two positive ions, the fractional ion abundance cannot be uniquely determined from M_{eff} alone. For example, if the ion components are H^+, He^+, and O^+, we have three unknowns in the two equations that are available.

$$\frac{1}{M_{eff}} = \alpha(H^+) + \frac{\alpha(He^+)}{4} + \frac{\alpha(O^+)}{16} \qquad \text{(A9)}$$

and

$$\alpha(H^+) + \alpha(He^+) + \alpha(O^+) = 1 \qquad \text{(A10)}$$

where $\alpha(H^+)$ = the fractional abundance of H^+, etc.

Nevertheless, for an ionosphere containing three species, some useful bounds can be obtained. Obviously if $M_{eff} < 4$, some H^+ must be present and if $M_{eff} > 4$, some O^+ must be present. Suppose, for example, that $M_{eff} = 2$. Then the percent H^+ will be greatest if no He^+ is present, and least if no O^+ is present. Evaluating these cases, we find that for $M_{eff} = 2$ the percent H^+ is bracketed between 46.7 and 33.3 percent.

Some characteristics of the wave at lower hybrid resonance can be deduced from equation 20, p. 11 of Stix [1962]. It follows from the third line of the equation that for phase propagation perpendicular to the impressed magnetic field, the electric field of the wave must lie in a plane perpendicular to the impressed magnetic field and, from the second line of the

same equation, that as $f \to f_{LH}$, the direction of the electric field becomes longitudinal, i.e., along the wave normal. Using the results of Stix, it is also easy to show that for propagation perpendicular to the impressed magnetic field, as $f \to f_{LH}$, the ratio of the wave's magnetic to electric field tends to zero, i.e., the field becomes "electrostatic." This conclusion may, however, not be valid in a "warm plasma" [Fredricks, 1968].

REFERENCES

Barrington, R.E., and J.S. Belrose, Preliminary results from the very-low-frequency receiver aboard Canada's Alouette satellite, Nature, 198, 651-656, 1963.

Barrington, R.E., J.S. Belrose, and D.A. Keeley, Very-low-frequency noise bands observed by the Alouette 1 satellite, J. Geophys. Res., 68, 6539-6541, 1963.

Barrington, R.E., J.S. Belrose, and G.L. Nelms, Ion composition and temperatures at 1000 km as deduced from simultaneous observations of a VLF plasma resonance and topside sounding data from the Alouette 1 satellite, J. Geophys. Res., 70, 1647-1664, 1965.

Belrose, J.S., and R.E. Barrington, VLF noise bands observed by the Alouette I satellite, Radio Science, 69D, 69-76, 1965.

Binsack, J.H., Plasmapause observations with the M.I.T. experiment on IMP2, J. Geophys. Res., 72, 5231-5237, 1967.

Booker, H.G., and R.B. Dyce, Dispersion of waves in a cold magneto-plasma from hydromagnetic to whistler frequencies, Radio Science, 69D, 463-492, 1965.

Brace, L.H., and B.M. Reddy, Early electrostatic probe results from Explorer 22, J. Geophys. Res., 70, 5783-5792, 1965.

Brace, L.H., B.M. Reddy, and H.G. Mayr, Global behavior of the ionosphere at 1000 kilometers altitude, J. Geophys. Res., 72, 265-283, 1967.

Brice, N.M., and R.L. Smith, A very-low-frequency plasma resonance, Nature, 203, 926, 1964.

Brice, N.M., R.L. Smith, J.S. Belrose, and R.E. Barrington, Triggered very-low-frequency emissions, Nature, 203, 926-927, 1964.

Brice, N.M., and R.L. Smith, Lower hybrid resonance emissions, J. Geophys. Res., 70, 71-80, 1965.

Cain, J.C., I.R. Shapiro, J.D. Stolarik, and J.P. Heppner, A note on whistlers observed in the ionosphere, J. Geophys. Res., 66, 2677-2680, 1961.

Carpenter, D.L., Whistler evidence of a "knee" in the magnetosphere ionization density profile, J. Geophys. Res., 68, 1675-1682, 1963.

Carpenter, D.L., Whistler studies of the plasmapause in the magnetosphere, 1. Temporal variations in the position of the knee and some evidence of plasma motions near the knee, J. Geophys. Res., 71, 693-709, 1966.

Fredericks, R.W., Structure of generalized low frequency Bernstein modes from the full electromagnetic dispersion relation, to be published in J. Plasma Phys., 2, 1968.

Gurnett, D.A., and B.J. O'Brien, High-latitude geophysical studies with Injun 3. 5. Very-low-frequency electromagnetic radiation, J. Geophys. Res., 69, 65-89, 1964.

Gurnett, D.A., A satellite study of VLF hiss, J. Geophys. Res., 71, 5599-5615, 1966.

Guthart, H., T.L. Crystal, B.P. Ficklin, W.E. Blair, and T.J. Yung, Proton gyrofrequency band emissions observed aboard OGO 2, J. Geophys. Res., 73, 3592-3596, 1968.

Hagg, E.L., Electron densities of 8-100 electrons cm^{-3} deduced from Alouette II high-latitude ionograms, Can. J. Phys., 45, 27-36, 1967.

Katsufrakis, J., Differences between the VLF magnetic and electric field spectra of the lower hybrid resonance (LHR) emissions and associated phenomena, paper presented at Spring URSI Meeting, Washington, D.C., April, 1968.

Kawashima, N., Demodulation of amplitude modulated RF waves in a plasma at resonance, NASA-Goddard Space Flight Center Report No. X-615-67-377, August, 1967.

McEwen, D.J., and R.E. Barrington, Some characteristics of the lower hybrid resonance noise bands observed by the Alouette I satellite, Can. J. Phys., 45, 13-19, 1967.

Osborne, F.J.F., F.H.C. Smith, R.E. Barrington, and W.E. Mather, Plasma-induced interference in satellite v.l.f. receivers, Can. J. Phys., 45, 47-56, 1967.

Scarf, F.L., G.M. Crook, and R.W. Fredricks, Preliminary report on detection of electrostatic ion waves in the magnetosphere, J.Geophys.Res., 70, 3045-3060, 1965.

Scarf, F.L., G.M. Crook, and R.W. Fredricks, Survey of VLF electric fields in the magnetosphere with the polar orbiting spacecraft, 1964-45A, Radio Science, 1, 939-956, 1966.

Scarf, F.L., R.W. Fredricks, and G.M. Crook, Detection of electromagnetic and electrostatic waves on OV3-3, J. Geophys. Res., 73, 1723-1745, 1968.

Shawhan, S.D., VLF ray tracing in a model ionosphere, Ph.D. thesis, Dept. of Physics and Astronomy, University of Iowa, 1966.

Shawhan, S.D., and D.A. Gurnett, VLF electric and magnetic fields observed with the Javelin 8.45 sounding rocket, Department of Physics and Astronomy, University of Iowa, Report 68-20, March, 1968.

Smith, R.L. and N.M. Brice, Propagation in multicomponent plasmas, J. Geophys. Res., 69, 5029-5040, 1964.

Smith, R.L., L. Kimura, J. Vigneron, and J. Katsufrakis, Lower hybrid resonance noise and a new ionospheric duct, J. Geophys. Res., 71, 1925-1927, 1966.

Smith, R.L., and J.J. Angerami, Magnetospheric properties deduced from OGO 1 observations of ducted and non-ducted whistlers, J. Geophys. Res., 73, 1-20, 1968.

Stix, T.H., The Theory of Plasma Waves, McGraw-Hill Book Company, New York, 1962.

Taylor, H.A., H.C. Brinton, and C.R. Smith, Positive ion composition in the magnetoionosphere obtained from the Ogo-A satellite, J. Geophys. Res., 70, 5769-5781, 1965.